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PRESSURE CONTROL IN DISTRICT METERING AREAS WITH BOUNDARY AND INTERNAL PRESSURE REDUCING VALVES

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Abstract

Despite operational improvements over the last 10-15 years, water utilities still are losing a significant amount of potable water from their networks through leakage. The leakage is managed on the one hand by reactive and proactive maintenance and on the other hand by pressure control to reduce background leakage from connection and joints. This paper is based on experience from the Process Control – Water Software Systems group which was involved in many pressure control projects and the current Neptune project (www.neptune.ac.uk). A fast and efficient method to calculate time schedules and flow modulation curves is presented. Both time and flow modulation can be applied to a single inlet DMA. Time modulation can be applied to a multi-inlet district metering area (DMA) but this is not always possible for flow modulation due to the risk of hunting. It is convenient to distinguish between boundary and internal pressure reducing valves (PRVs), the decision variable for a boundary valve is a PRV set-point whereas for the internal valves it is a valve resistance. The resistance is then automatically translated into a set-point for field implementation.

The time modulation methodology is based on solving a nonlinear programming problem with equality constraints represented by a hydraulic model with a pressure dependent leakage term and inequality constraints representing operational requirements (e.g. pressure at critical nodes). The cost of boundary flows which include leakage flows is minimized. An extended content model with pressure dependent leakage is simulated to provide a starting point for quick convergence. Optimal time schedules are converted into flow modulation curves by plotting scatter plots of flows against heads.

The algorithm has been implemented as a module in the FINESSE package and allows complete pressure control tasks to be solved. A user needs to provide an hydraulic model, leakage information and leakage characteristic – leakage area and the exponent in the pressure power law. The program calculates time schedules and also flow modulation curves for single and multi-inlet PRVs.

Evaluation of optimal control strategies and benefit analysis in terms of leakage reduction for two case studies provided by Yorkshire Water Services is included.

1. INTRODUCTION

Globally, water demand is increasing while the recourses are diminishing. The water loss from water distribution systems (WDSs), has long been a feature of the WDS operations management and occurs in all WDSs, only the quantity of loss varies and depends on the physical characteristics of the pipe network, and the level of technology and expertise applied to controlling this loss. In Addis Ababa, Ethiopia, nearly 50% of the produced water is lost (Desalegn, 2005), the same level is reported for the city of

Mutare, Zimbabwe (Marunga *et al.*, 2006). In many Asian cities 46% is non revenue water of which over 75% is real losses (Rogers, 2005). In the UK, water utilities estimate the total loss at over 23% (3575 Ml/d) of the total input (OFWAT, 2006).

Managing and controlling water loss is becoming very important issue in this age of rapidly growing demand and scarcity of the water resources brought by climate changes that bring droughts to many locations over the world (Houérou, 1996; Bergkamp *et al.*, 2003). Due to today's high water production, treatment and transmitting costs and rates, many water utilities have been developing new strategies to minimise losses to an economic and acceptable level in order to preserve valuable water resources and to minimise operating expenditures.

Water companies practise one or more of the leakage management strategies: namely general pipe rehabilitation, direct detection and repair of existing leaks, and operational pressure management. General pipe rehabilitation is the most costly and long term action undertaken to improve a number of different factors including leakage and water quality (Engelhardt *et al.*, 2000; Clark *et al.*, 2002). Direct detection and repair of existing leaks is one of the most efficient policies, that is used to prevent the high level of losses from bursts but it doesn't reduce the background leakage caused by small seepages from connections and joints. Many algorithms have been developed to predict, localise and quantify the leakage in WDSs (Wu and Sage, 2006; Koppel *et al.*, 2007). Pressure management is now recognised as one of the most cost effective methods to reduce leakage in water networks and is implemented by most water companies (Araujo *et al.*, 2003) and at the same time minimising the risk of further leaks by smoothing pressure variations. Many researchers have developed and implemented various methods and algorithms to optimise the operational pressure, and the results showed that the leakage can be reduced by up to 60%. Miyaoka and Funabashi, (1984) developed and implemented an optimal pressure regulator and achieved an average rate of the leakage reduction of about 22%, but the leakage model was not considered. Jowitt and Xu, (1990) developed a linear algorithm for the determination of control valve settings to minimise leakage, the overall reduction in leakage was about 20%. Vairavamoorthy and Lumbers, (1998) described an optimisation method to minimise leakage in water distribution systems through the effective settings of flow reduction valves and reduced the water leakage substantially. Alonso *et al.*, (2000) presented a parallel computing based software demonstrator for simulation and leakage minimisation. The optimisation problem of leakage minimisation using PRVs was solved by means of sequential quadratic programming and the leakage was reduced by 25% to 60% of its original values. Burn *et al.*, (2002) analysed the effect of employing pressure management techniques on the cost of WDSs, which increases the savings by a further 20-55%. Girard and Stewart (2007) implemented the pressure and leakage management strategies on the Gold Coast, Australia, and the results revealed there was a good opportunity to achieve significant water savings. Marunga *et al.*, (2006) implemented a pressure management in Mutare, Zimbabwe, the results showed that an operating pressure reduction from 77 m to 50 m resulted in 25% reduction in the total leakage.

This paper is based on the experience of the Process Control – Water Software Systems group which was involved in many pressure control projects and the current Neptune project (www.neptune.ac.uk). During implementation of a pressure control scheme both steady state and dynamic aspects should be considered (Brunone and Morelli, 1999; Ulanicki *et al.*, 2000; Prescott and Ulanicki, 2003; 2008) and there are work packages in the project to investigate these aspects. Furthermore, in the Neptune project the pressure management is considered jointly with energy management because both problems are interlinked. The steady state aspects ensure that pressure reducing valve (PRV) set-points are changed according to changing demands to minimize background leakage and to satisfy pressure at critical points. The dynamic aspect considers preventing excessive pressure hunting (oscillations) across a network caused by interactions between modulating valves and transients in water networks. This paper presents the results of steady state pressure control achieved in the project.

A general method of calculating PRV set-point schedules for the boundary and internal valves is presented taking into account pressure dependent leakage. A simple method of evaluating leakage model parameters from the minimum night flow is also presented. The paper discusses what conditions need to be satisfied to translate optimal schedules into flow modulation curves. This is an important issue because it is not always possible for flow modulation due to the risk of hunting. However, both time and flow modulation can be applied to a single inlet DMA.

2. PROBLEM OUTLINE

Currently, it is a common practice for water utilities to divide the water distribution networks into district metering areas (DMA) with closed boundaries except for a small number of metered inlets and outlets. This structure facilitates applying pressure management schemes to those areas. Current control strategies operate output pressure of the PRV, which control inlet pressures to the DMA. The outlet pressures of the PRVs are based on the minimum values, which can satisfy DMA minimum service pressures for customers with a safety margin. Low operational pressures result in reduced leakage and minimisation of the risk of bursts.

In this work, an algorithm for the optimum scheduling of the outlet pressures of the boundary PRVs as well as the internal PRVs is developed to minimise and smooth the operational service pressure across the DMA. This algorithm is based on calculating the optimal PRVs schedules for given demand incorporated with the leakage model. In the current work, the algorithm of the pressure control is limited to the steady state condition. This means, changes of PRV settings cause instantaneous changes of flows and heads in the network. The PRV set-point schedules are calculated over a given period of time, the novelty of the approach presented here is inclusion of both boundary and internal PRVs in the problem formulation. The components of the optimal pressure control problem are the objective function, the hydraulic model of the network taking into account the leakage model, and operational constraints.

3. EXENDED HYDRAULIC MODEL

A water distribution system consists of a group of interconnected nodes connected through elements such as pipes, valves and pumps. Each element in the network is represented by a mathematical equation which describes a relationship between the element flow and the heads at the origin and destination nodes. The system of equations also includes the mass conservation and energy conservation laws.

The main components in a DMA are pipes which can be described by many different formulae. The most common are the Darcy-Weisbach, Colebrook-White, and Hazen-Williams equations (White, 1999). The Darcy-Weisbach equation combined with the Colebrook-White formula provides a more accurate model than the Hazen-Williams representation over wide range of flow regimes but requires more computational effort; the Hazen-Williams equation has an advantage of computational simplicity and therefore receives wider application.

Components and Nodal Heads

The mixed model is used to represent DMA equations in which the branch flows and nodal heads are the unknown variables (Brdys and Ulanicki, 1994). The head-flow relationship for a pipe element with an origin node *i* and the destination node *j*, can be expressed by Hazen-Williams formula.

$$h_i - h_j = R_{ij} \cdot q_{ij} \cdot \left| q_{ij} \right|^{0.852} \tag{1}$$

For a valve element connecting node *i* as an origin and node *j* as a destination node, the following equation (2) holds

$$h_i - h_j = K_{ij}(v_{ij}) \cdot R_{ij} \cdot q_{ij} \cdot \left| q_{ij} \right|^{0.852} \tag{2}$$

Where h_i and h_j = head in [m] at node *i* and *j*, respectively; R_{ij} = the resistance of either a pipe or a valve element; $K_{ij}(v_{ij})$ = the resistance modification coefficient related to the valve opening v_{ij} , the fully opened valve is represented by $K_{ij}(v_{ij})=1$, and the completely closed valve is represented by a very big value theoretically equal to infinity; q_{ij} = the flow in [l/s] from node *i* to node *j* through the element.

A DMA will contain a set of boundary nodes I_b which are connected to external nodes (which do not belong to a DMA) through pressure reducing valves (PRVs).

Mass Balance At Nodes

The mass balance equation for a connection node (non-reservoir node) *i*, can be written as.

$$\sum_{k \in N_i^+} q_{ki} - \sum_{k \in N_i^-} q_{ik} = d_i + l_i \tag{3}$$

Where N_i^+ = a set of nodes connected to node *i* as a destination node, and N_i^- = a set of nodes connected to node *i* as an origin node; d_i and l_i = demand and leakage flows allocated to node *i*, respectively.

Leakage Model

The pressure control analysis requires an enhanced hydraulic model, which incorporate pressure dependent leakage terms. The leakage is usually split into background and burst components. The background leakage represents small seepages through numerous connections, joints and fittings. It depends on the operational service pressure in pipes and the purpose of the pressure control is to reduce this component.

Several mathematical models relating the leakage and the operating pressure based on experimental results have been proposed (Brown, 2007; Koppel *et al.*, 2007; Giustolisi *et al.*, 2008).

The leakage-pressure relationship as shown in equation (4) is assumed and is added to the standard hydraulic equations (1) (2) and (3) to create an extended hydraulic model

$$l_i = k_i \cdot p_i^{\alpha} = k_i \cdot (h_i - H_i)^{\alpha} \tag{4}$$

where k_i = the leakage coefficient; α = the leakage exponent and H_i = the elevation of node *i*. The leakage is assumed to be distributed over the nodes, which have a demand and the set of these nodes will be denoted by I_d. The leakage exponent α ranges from 0.5 to 2.5 depending on many factors described in the literature (Jowitt and Xu, 1990; Germanopoulos, 1995; Alonso *et al.*, 2000; Noack and Ulanicki, 2006; Ulanicki and Prescott, 2006). In the current study the exponent is assumed to be $\alpha = 1.1$, whilst coefficient k_i depends on the demand at each node i.e. is related to the number of customers.

Estimation of the Parameters of the Leakage Model

The UK water companies do not generally provide detailed information about the leakage model and here a simple approach is proposed for evaluating the leakage model parameters from the minimum night flow (MNF). The estimated total value of network background leakage is distributed among the nodes in the network model proportionally to the number of properties connected to each node or the demand of that node.

It is assumed that the total leakage is equal to MNF, $q(t_{\min})$, which occurs at time t_{min} as shown in equation below.

$$q(t_{\min}) = \sum_{i \in I_d} l_i(t_{\min}) = \sum_{i \in I_d} k_i \cdot p_i(t_{\min})^{1.1} = \sum_{i \in I_d} \beta \cdot d_i(t_{\min}) \cdot p_i(t_{\min})^{1.1} \tag{5}$$

where $d_i(t_{\min})$ and $p_i(t_{\min})$ denote the demand flow and pressure of node *i* at time $t_{\min}$, respectively.

The coefficient k_i is proportional to the demand flow of node *i* at the time of the MNF, $t_{\min}$.

$$k_i = \beta \cdot d_i(t_{\min}) \tag{6}$$

By combining equations (5) and (6) the constant factor β can be computed according to the equation below.

$$\beta = \frac{q(t_{\min})}{\sum_{i \in I_d} d_i(t_{\min}) \cdot p_i(t_{\min})^{1.1}} \tag{7}$$

4. OPTIMISATION PROBLEM

Objective Function

The control objective is for each time step to minimise the cost of the boundary flows

$$\phi_t = \sum_{i \in I_b} c_i(t)\, q_i(t) \qquad t \in T \tag{8}$$

where $c_i(t)$ = the price per unit of volume including the cost of production, treatment and transport at time t; T = the set of time steps. Because the demands are assumed not to be affected by the pressure, minimising the total cost of the boundary flows is equivalent to minimising the leakage flow. The optimisation problem is solved independently at each time step as there is no storage in the system.

Equality Constraints

Equations (1)-(4) of the extended hydraulic model are the equality constraints in the optimisation problem.

Inequality Constraints

A set of operational constraints should ensure feasible operation of the physical system. The pressure (head) constraints are to secure minimum service pressure of 15-20 meters and to avoid excessively high pressures:

$$h_{i,\min} \le h_i \le h_{i,\max} \tag{9}$$

The pressure limits $h_{i,\min}, h_{i,\max}$ may depend on the node type, e.g. constraints at critical nodes are tighter than at normal connection nodes and the limits at the boundary nodes may be imposed by external conditions.

The boundary flow constraints are to force the flow direction into the network and to impose upper bounds coming from the external conditions.

$$0 \le q_i \le q_{i,\max} \quad i \in I_b \tag{10}$$

Decision Variables

The decision variables in the formulated optimal pressure control problem are the boundary heads h_i, $i \in I_b$ representing the boundary PRV set-points which appear in equation (1) and the resistance modification coefficient $K_{ij}(v_{ij})$ for the internal PRVs which appear in equation (2). Subsequently, the PRV resistance is translated into the PRV set-point for the control implementation.

5. TIME VERSUS FLOW MODULATION IMPLEMENTATION

The optimisation problem is solved T times and provides optimal time schedules for the PRV set-points $\hat{h}_i(t), i \in I_{PRV}$, where I_{PRV} =the set of boundary and internal PRVs, the corresponding PRV optimal flows will be denoted by $\hat{q}_i(t)$. The PRV can be actuated remotely or the schedules can be stored locally in individual PRVs in both cases an electronic controller is required which will adjust the set-point accordingly.

Optimal flow modulation rules can be obtained by eliminating time from the optimal solutions and producing functional relationships between the optimal heads (set-points) and the flows ('scatter plots')

$$\hat{h}_i = f_i(\hat{q}_{i_1}(t), \hat{q}_{i_2}(t), ..., \hat{q}_{i_{I_{PRV}}}(t)), \quad i \in I_{PRV} \tag{11}$$

In a general case the set-point of the *i-th* PRV depends on the flows through all PRVs. Implementation of such a strategy would require a central controller and/or communication links between all PRVs so that each PRV controller can read flow values from all other PRVs to calculate the set-point.

One can pose the question about the possibility of implementing local modulation curves, i.e. decomposition of the control law (11), where the set-point depends only on the local flow.

$$\hat{h}_i(t) = f_i(\hat{q}_i(t)) \tag{12}$$

The practical answer to this question can be obtained by plotting an individual scatter plot $(\hat{h}_i(t), \hat{q}_i(t))$ for each PRV. If the points form a smooth curve (a functional relationship) then the individual flow modulation is possible. If they form a cloud of points i.e. for a given flow a head is not determined uniquely (lack of a functional relationship) the individual flow modulation is not possible and either time schedules or centralised flow modulations should be implemented. In this case a forced implementation of individual modulation curves will result in significant hunting and instabilities in the water distribution system.

6. THE SOLUTION OF THE PRESSURE OPTIMISATION PROBLEM

The described optimal PRV scheduling algorithm is embedded as a module into the FINESSE software package (Rance *et al.*, 2001). The module is coded using the advanced mathematical modelling language known as General Algebraic Modelling System (GAMS) (Rosenthal, 2007) and uses a non-linear programming solver called CONOPT. The solution is in the form of schedules for the PRV set-points. In addition, the results can be post-processed and represented as a modulation curve (valve flow against optimal outlet pressure) (Ulanicki, 2000).

The PRV scheduling algorithm can be used for off-line planning studies such as assessing the benefits of introducing the leakage management or for on-line pressure control, which may be implemented in either predictive control or feedback control as a real time control scheme (Ulanicki *et al.*, 2000; Drewa *et al.*, 2007). Predictive control calculates the optimal PRV schedules at each interval of time by the optimal scheduling algorithm, using updated demand prediction. The method could be considered as a time modulation scheme and requires advanced PRVs equipped with controllers that accept time profiles. The feedback control structure uses controlled PRVs by sensing its flow, in such PRVs, the outlet pressure (set-point) depends on the valve flow.

It is assumed that the standard information required by an hydraulic model is given together with the information about the minimum night flow and the unit prices of the boundary flows. The decision variables are the set-points for the boundary valves and resistance coefficients $K_{ij}(v_{ij})$ for the internal valves. The constraints are the network hydraulic equations and the operational constraints of the minimum and maximum pressures. The objective function represents the cost of the boundary flows. FINESSE is used to build the hydraulic model of the network and to define the pressure control problem, the GAMS input file is generated and the nonlinear programming solver CONOPT is called to solve the optimisation problem. In order to accelerate the convergence of the optimisation algorithm the initial solution is obtained from the simulation of the current PRV settings. The hydraulic model of the network is simulated by using the extended content model including pressure dependent leakage and is solved by using the optimisation technique, the original content model was formulated in (Collins *et al.*, 1978). In the following section, two case studies are solved to assess the performance of the developed algorithm.

7. CASE STUDIES

E067 Case Study

A DMA in North Yorkshire, UK called E067 is the first case study. The zone is predominantly urban domestic/light industrial. The total mains length is 6.272 km, with 10 valves enclosing the zone. The zone contains two pressure reducing valves, the first, PRV1 located upstream of the inlet meter and second PRV2 located downstream as illustrated in Figure 1. The zone contains 409 domestic and 11 commercial properties with an annual demand higher than 400m^3 each. There are inlet flow and pressure measurement points, and a monitored pressure measurement at a critical point. The DMA E067 has water supplied via the boundary inlet node, which has a variable inlet head ranging from 135 m in the night to 115 m at the maximum demand time. The total measured inflow to E067 is around 0.5 l/s during the night and increases to reach its maximum value of 3.5 l/s at 7:00 o'clock, then decreases to the average level of 2 l/s during the day. The current settings are: for boundary PRV1, 110.88m; and for internal PRV2, 110.05m.

Optimal schedules for PRV1 and PRV2 set-points have been calculated using the developed module in FINESSE and leakage reduction has been evaluated. The optimisation has aimed to reduce the inlet flow with pressure constraints at the critical node at or above 20 m. The optimal outlet head of the boundary PRV1, is approximately constant in time as depicted in Figure 2, and equal to 110 m, which is very close to the current setting. The optimal schedule of the PRV2 (internal PRV) has an almost constant value of 82.5 m. The total savings in the inlet flow are 5.7% mainly due to the reduced settings of PRV2. Figure 3 shows the difference between the current and the optimal inlet flow to the DMA, 0.102 l/s on average which represent 30% of the original leakage flow. The minimum pressure of 20m at the critical point is maintained over the whole time horizon. The application of flow modulation is not necessary as the optimal PRV schedules are constant, this is due to very low head losses across the DMA.

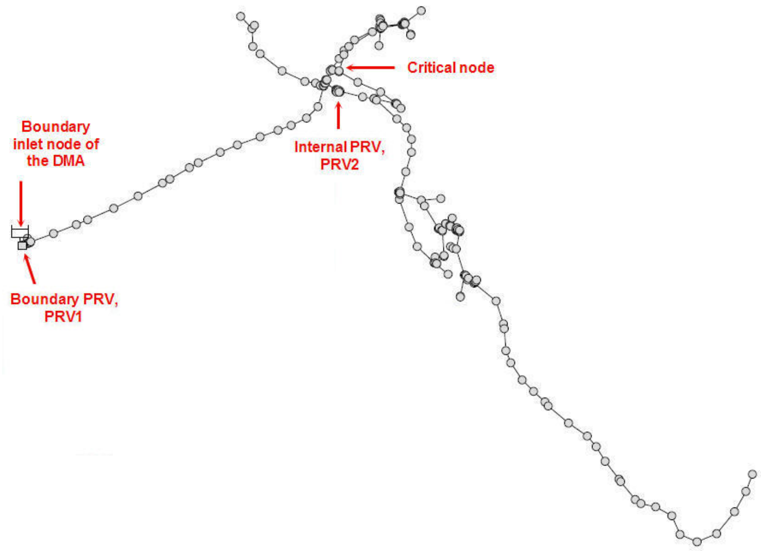

Figure 1. Layout of the E067 DMA

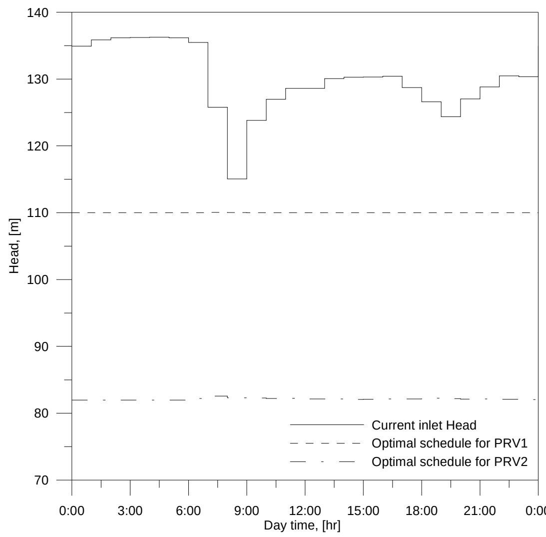

Figure 2. Inlet head and optimal schedules for the boundary and internal PRVs

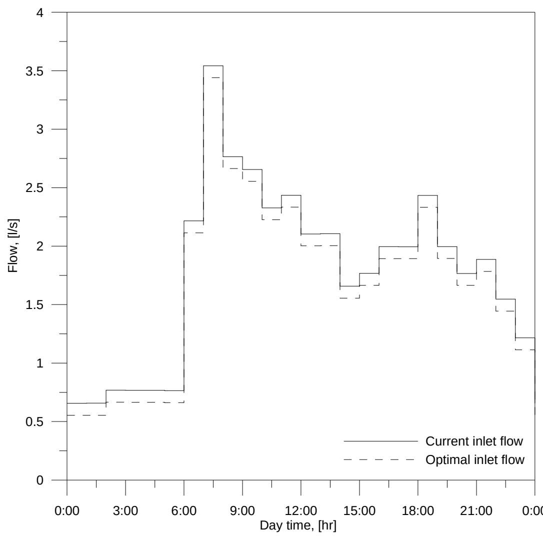

Figure 3. The current imported and optimal flow to the DMA

E093 Case Study

DMA E093 located in Yorkshire, UK, is used as the second case study. The DMA has one boundary PRV and 4 internal PRVs as shown in Figure 4. The area contains 171 domestic properties and 42 commercial properties of which 40 have a demand greater than 200 m^3/year. There is one inlet flow and pressure measurement point. The DMA E093 boundary head changes from 171.75 m at night to 164 m at the maximum demand time during the day. The total measured inflow is around 1.9 l/s during the night and increases to 4.6 l/s at 7:00 o'clock and then decreases to the average level of 3.5 l/s during the day. Currently, PRV1 is not active (fully open), while PRV2, PRV3, and PRV4 have been set to reduce the outlet head to 122.98, 105.05, and 127.8 m, respectively.

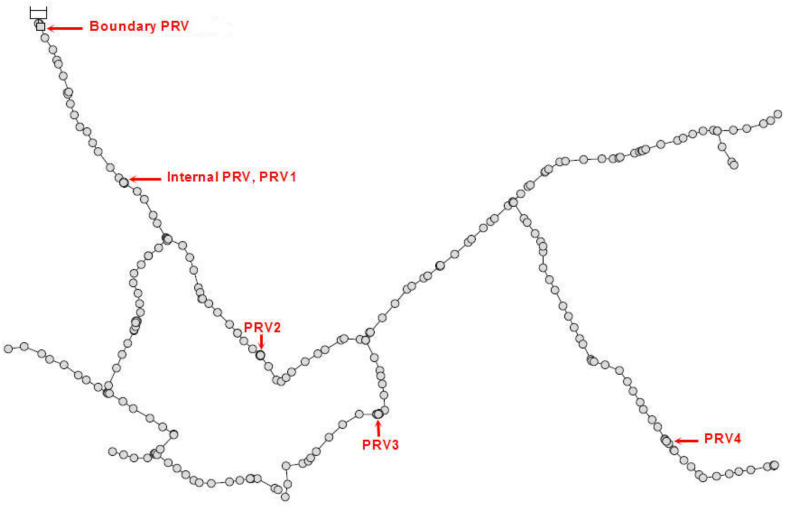

Figure 4. Layout of E093 DMA

The DMA E093 pressure is optimised and the results are shown in Figure 5 where the optimal schedule of the boundary PRV is varying between 139.5m and 143m. The optimal schedules of the internal PRVs are depicted in Figure 6, the optimal set-points for PRV1, PRV3, and PRV4 are almost constant in time and assume the values of 140.5m, 100.5m, and 97 m, respectively. The PRV2 set-point varies between 116 and 120.5 m. The implementation of the optimal schedules saves 36.2 m^3/day and reduces the leakage by 45% as shown in Figure 8.

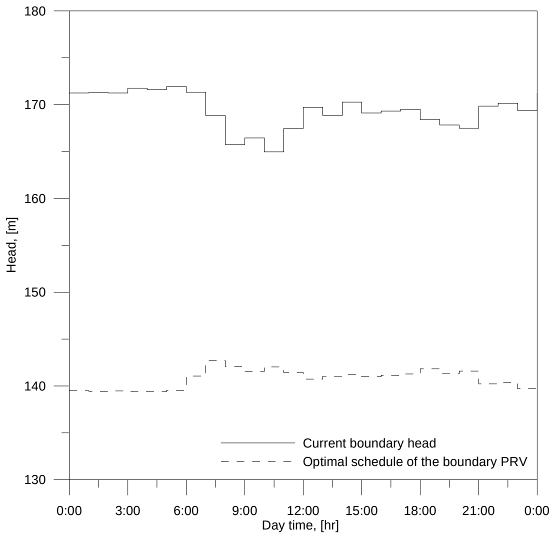

Figure 5. The current head of the boundary node and the and optimal schedule of the boundary PRV of E063 DMA

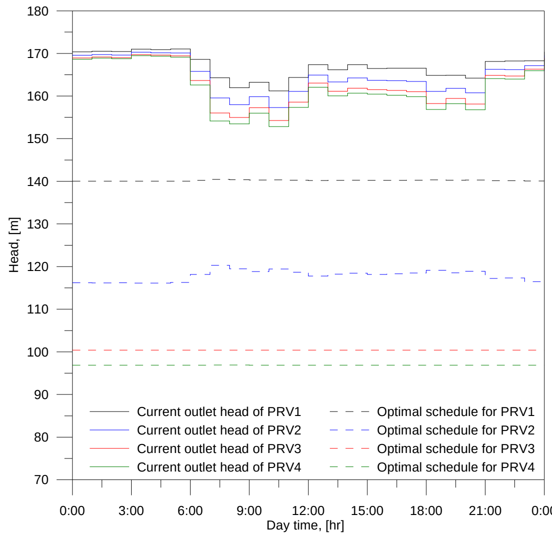

Figure 6. The current and optimal schedules of the internal PRVs of E063 DMA

After plotting scatter graphs for the boundary node and PRV2 shown in Figure 7 it appeared that they represent smooth curves and the decomposed flow modulation control can be applied in this case.

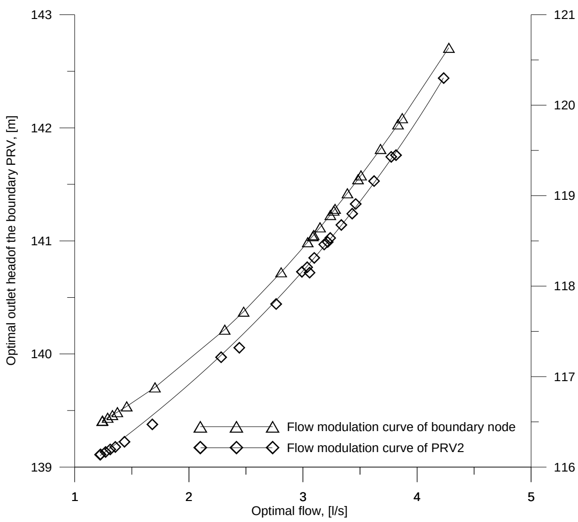

Figure 7. The flow modulation curves for the two PRVs

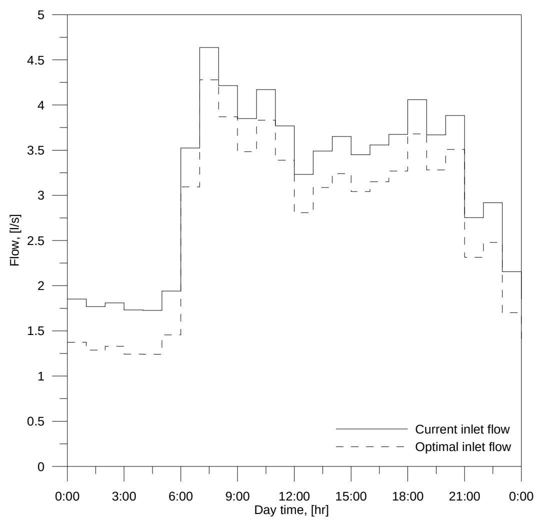

Figure 8. Current and optimal inlet flow to the E063 DMA

8. CONCLUSION

A fast and efficient method to calculate the optimal time schedules and flow modulation curves for the boundary and internal PRVs has been presented in order to minimise the leakage in water distribution systems. The cost of boundary flows which include leakage flows is minimised. An extended content model with pressure dependent leakage is simulated to provide a starting point for quick convergence. The boundary and internal PRVs have been treated differently, the decision variable for a boundary valve is a PRV set-point whereas for the internal valves is a valve resistance. The resistance is then automatically translated into a set-point for field implementation. The optimisation problem is solved by a non-linear programming solver called GAMS/CONOPT. The program calculates time schedules for single and multi-inlet DMAs. The optimal schedules can be translated into centralised flow modulation rules where a set-point for one PRV depends on flows through all other PRVs. For weakly interacting PRVs it is possible to obtain decomposed flow modulation curves where the set-point depends only on the local flow.

The algorithm has been implemented as a module in the FINESSE package and allows complete pressure tasks to be solved. A user needs to provide a hydraulic model and leakage information (at least minimum night flow).

Evaluation of optimal control strategies and benefit analysis in terms of leakage reduction for the two case studies provided by Yorkshire Water Services is included. The DMA E067, which has one boundary and one internal PRV, is optimised and it has been found that, the leakage can be reduced by 30%. Due to the constant optimal pressure schedules of the PRVs, the flow modulation control is not applicable in this case. In another case study, DMA E093, which has four internal PRVs, can achieve a leakage reduction by 45%. The decomposed flow modulation control has been applied on the boundary node as well on the PRV2 of the DMA E093.

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